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A through-life approach to developing high-performance microsystems

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Abstract

This paper presents an assessment of the feasibility of a through-life approach for the development of high performance microsystems (HPMs) – microsystems, or microelectromechanical systems (MEMS) designed to operate in extreme conditions. It introduces HPMs, and their applications and presents reliability as the main through-life challenge to their market growth. It characterizes reliability challenges in HPMs and details the current understanding of failure modes in HPMs. It describes progress in failure prediction in HPMs and discusses future challenges. Finally, it summarizes why a general Design for Reliability approach would be advantageous for HPMs and summarizes progress in implementing such an approach.

Keywords: microsystems; microelectromechanical systems; MEMS; high performance; through-life; realiability; failure; failure prediction; design for reliability;

1. Introduction

This paper summarizes the feasibility of a through-life engineering approach to "high performance microsystems". It introduces the concept of high performance microsystems and current concerns with regards their reliability. It characterizes reliability challenges in HPMs. It details the current understanding of failure modes in HPMS and their relationship with structural complexity. It describes progress in failure prediction in HPMs and discusses future challenges. Finally, it summarizes why a general Design for Reliability approach would be advantageous for HPMs and summarizes progress in implementing such an approach.

1.1. High Performance microsystems

Applications of microsystems technology have rapidly increased in the recent years in areas such as automotive, healthcare, portable devices, energy and defence. Examples include sensors and actuators, gyros, inkjet heads, accelerometers, microfluidic devices. Applications are usually referred to in the literature as microelectromechanical systems (MEMS). In the context of this paper, "microsystems" and "MEMS" will be used interchangeably.

The MEMS market grew 17% in 2011 to reach \$10.2bn. The top 30 companies account for almost 80% of total MEMS packaged device sales worldwide [1]. The value of MEMS-based products is estimated to reach \$40 billion in 2015 and \$200 billion in 2025, with much of the growth to come from products that are beyond current manufacturing techniques [2,3]. Recent years have witnessed a demand shift towards portable communication devices, such as smart phones (\$2.25bn in revenues for this sector alone in 2011 [4,5]).

Technology push in MEMS has been driven by the introduction of novel microfabrication techniques, particularly with mass-fabrication capabilities, and the implementation of new materials beyond silicon [6].

High performance microsystems are those designed to withstand severe operating conditions. Their existence has been enabled by this introduction of novel microfabrication techniques. Typical examples include microfluidic reactors, micro-heat exchangers and micromechanical components.

Operating condition limits vary with application. Space microsystems can be exposed to temperatures as high as 2000°C and mechanical shock loads that can be up to 103 g.

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Pressures in the order of hundreds of MPa could be expected inside microsystems. Other extreme conditions include vibration, radiation, cyclic thermal and mechanical loading, and exposure to corrosive chemicals or high temperature fluids such as molten glass.

An interesting example of HPMs is the fast developing area of 'power-generating' microsystems, aimed at developing energy sources that are compact, lightweight, long-life and powerful [7,8] with typical power output between milliwatts to watts [9]. There are four main categories of power-generation HPMs: micro-combustors; micro-heat engines/gas turbines; micro-rockets/thrusters and micro-fuel cells [11].

Potential applications of power-generating microsystems include [9-14]:

- Microelectromechanical systems (MEMS), such as powering sensors and transmitters
- Portable electronics, such as batteries for laptops, cameras and mobile phones
- Defense applications, such as powering micro unmanned aerial vehicles (UAVs), micro-airplanes and military exoskeletons
- Aerospace applications, such as microsatellite primary propulsion and attitude control
- General mechanical drive applications, such as micro-rovers and micro-robots

Among power-generating microsystems, microcombustors have showed potential growth since their early developments at MIT [14-16]. Several reviews of progress can be found in the literature [9,11,13,17-19].

1.2. Reliability concerns in HPMs

Due to the relatively low readiness level of the technology, the research focus in HPMs is directed to design or microfabrication. Issues of device reliability and service life prediction are therefore left to later development stages. This is likely to result in extra development time and costs. Therefore, a different approach is needed for developing HPMs that takes into consideration the full life-cycle of the device and the effect of operation conditions on their reliability and life expectancy.

All HPMs are developed specifically to withstand severe operating conditions, not only from within the devices themselves but also from the surrounding environment. Such devices are often expected to operate in conditions where there could be no access for maintenance or inspection, such as space shuttles or defense equipment, where reliability is a paramount requirement.

Therefore, developing HPMs should be centered around the whole life-cycle of the device rather than just on functionality. In order to progress the field of HPMs and realize its potential applications, a new approach is required where all development stages, such as design, materials selection, microfabrication (including assembly and packaging) and inspection are focused on ensuring a fault-free performance of the device in extreme conditions. This requires a reliability-based approach for developing HPMs, which aims at maximizing the lifetime of the device and minimizing failure risk during this life time.

Overcoming the challenge of reliability in HPMs therefore requires two main steps: to be able to predict failures and tackle potential reliability challenges before the actual production of the device; to develop a design for reliability (DfR) approach that would be integrated within the product-development process of the HPMs beside other design-for considerations, such as functionality, manufacturing and assembly

The following sections briefly discuss the state of the art in these areas. First reliability of HPMs is summarized. This is followed by a summary of causes of failure in HPMs. Following this, the prediction of failure is addressed, and, finally, designing for reliability is discussed.

2. Reliability of HPMs

2.1. The need for HPM reliability

Reliability in general is the sum of all characteristics of a device concerning its ability to achieve specified requirements under well-defined conditions over a given period of time [20]. It can be defined as the probability that an item can perform its intended function for a specified interval under stated conditions [21-23]. Essentially, reliability indicates that a product performs as specified in the datasheet [6]. In that sense, assessing the reliability of a product is about describing how its quality changes over time.

It is only in the past few years when MEMS technologies and device performance have advanced sufficiently, and the applications have become so critical, that researchers have paid more attention to the issues of reliability and long-term survivability [24]. Focusing on reliability has become particularly important for a number of reasons [20,22,25-27]:

- MEMS applications started to appear in areas where failure is not acceptable, such as medical devices, space applications [28] and automotive safety systems
- MEMS are integrated into systems, such as automotive sensors, with an average lifetime of 15 to 20 years.
- Cost considerations have become a significant driver, as in many cases MEMS reliability issues are postponed to later stages of product development, but the expenditure required to fix problems overlooked in an early phase increases drastically with product development
- Commercialization of MEMS: improving the reliability of MEMS accelerates the industrial take up of the technology; the current immaturity of the field is one of the factors hindering the commercialization of MEMS technology
- Competitiveness: MEMS reliability is important for competitiveness assessment in terms of meeting customer expectations by taking reliability into consideration during design stage

Due to the wide variety of designs, materials and microfabrication techniques, it is likely that MEMS require their own reliability models and test structures to be developed.

There is a general agreement that the area of MEMS reliability is still in its infancy, and that there is a lack of experience in systematic approaches to MEMS reliability [25,29].

2.2. HPM reliability challenges

Unlike other products or systems, HPM applications have specific characteristics that make them particularly challenging to characterize. Such unique characteristics are summarized as follows:

- Size: the micro-scale geometries and structures of MEMS affect the physics of the materials [30], which is not as fully understood at this scale as it is for conventional components. In addition, the surface area-to-volume ratio of a body is proportional to the reciprocal of its characteristic length. Therefore, as the size of a structure is reduced, surface phenomena (such as Van der Waals, electrostatic, capillary forces) dominate the behavior, and interaction, of structures as compared to volumetric effects (inertia and gravitational forces) [30]. On the positive side, the small sizes of MEMS improve their robustness, because the strength-to-weight ratio increases as the component volume decreases [20,27]. In addition, large variations in temperature do not cause large variations in component size at this scale [31]
- Materials: the diversity of materials integrated together, and their manufacturing techniques, are likely to generate different failure modes from traditional microelectronics or from mechanical systems [27,29]. In addition, data for material performance and mechanical properties at the micro-scale are often unavailable, and accurate measurement techniques and tests at the microscopic scale are difficult to perform and affect the repeatability of obtained data [29]
- Multiple domains: MEMS devices usually work across multiple domains (for example, electrical, mechanical, thermal, biological, optical, chemical, radiant, etc.), which results in a multiplicity of potential failure modes lying often at the boundaries of these domains [25,26,30]
- Diversity of applications: Many MEMS applications are in early development stages, so they are usually designed for specific applications using novel materials and micro-fabrication techniques. This diversity of application is a major challenge for MEMS reliability, because reliability tests are typically defined on an application-specific basis, and there are few generic test methods or standards [22,30]
- Lack of failure: Because of the lack of material and mechanical data at the micro-scale, qualification tests are likely to miss potential failure modes in MEMS devices, and therefore faulty devices might pass superficially stringent qualification tests, only to fail later [32]. In addition, predicting the lifetime of MEMS devices based on statistical sampling requires a relatively large amount of defective samples, which is usually unavailable [20]
- Variety of extreme conditions: Some tests have been developed for MEMS in extreme conditions, such as vibration or radiation in space applications [24,32] or shock forces in military applications [31]. However, such tests are in the early stages and are for specific devices. Other extreme conditions, such as caustic biofluids or corrosive substances are yet to be investigated [31]
- Range of testing: Some extreme conditions are beyond the current testing range of MEMS reliability. For example, several tests have been reported in the literature of thermal cycling in MEMS, but such tests are limited in range (e.g. between -40°C and 140°C in automotive sensors [20])

3. Failure in HPMs

A failure is defined as when the device does not perform anymore according to the specifications during functional or reliability testing or in the field [22], or it is also defined as the case when “a device or a system no longer performs the required functions under the stated conditions within the stated period of time” [29].

There are two main categories of failures [29,33]:

- Catastrophic (or irreversible) failures, which involves the total destruction of the device, rendering it completely inoperable
- Degradation failure, which consists of the device parameters operating outside then normal range of operation. This type of failure can be either permanent of reversible, depending on the specific failure mechanism

Failure modes, a term used interchangeably with failure mechanisms [33], usually refer to observable adverse effects (broken structure, cracked surface, plasticity mechanism, etc.) or directly measurable degradation exceeding the prescribed limits. Investigating failure modes in microsystems applications is essential for assessing and improving the reliability of the devices. This is because understanding how failure happens helps the designer to mitigate potential risks by reviewing the design, the selected materials and the manufacturing route to potentially eliminate failures and extend lifetime.

Many failures have been identified for MEMS devices and different classification methods have been proposed for MEMS failures. One classification is based on failure-location relative to the MEMS physical structure [20]:

- Microstructure: inherent mechanical and electrical properties, material properties, combination of materials (coefficient of thermal expansion, mechanical stress, chemical reaction, movable parts)
- Assembly and packaging: temperature range, media pressure, mechanical loading

Other classifications are based on the source of the failure relative to the life cycle of the MEMS device [25,26,29,30,32,34-36]:

- During design/fabrication: e.g. stiction, residual stresses, thermal loss, etc.
- During operation: e.g. stiction, fatigue, wear, creep, etc.

- Environmentally induced: e.g. particle contamination, vibration, humidity, ambient pressure, temperature changes, radiation

3.1. Failure and structural complexity

Failure in MEMS devices is highly dependent on the structure of the device, and MEMS devices that share the same degree of structural complexity typically share similar failure mechanisms [34]. One classification of MEMS devices puts them into two groups [29]:

- MEMS with moving parts and no impacting surfaces, for example, gyros, accelerometers and RF oscillators
- MEMS with moving parts with impacting surfaces. Examples include micro-mirror arrays and RF switches

Another commonly used classification system groups MEMS devices into four main classes [30,34,37]:

- Class I: devices in this class have mechanical elements but the elements do not move, for example, accelerometers, ink-jet printer heads, pressure sensors and strain gauges
- Class II: devices in this class have mechanical elements that move, but have no parts that rub or touch. Examples include gyros, comb drives, resonators and filters. They are typically susceptible to fracture, fatigue and creep
- Class III: devices in this class have moving, touching or impacting parts. Examples include digital micro-mirror devices, relays, valves, pumps. They are typically susceptible to shock, and vibration could be a concern due to impacting surfaces
- Class IV: devices in this category have moving, touching and rubbing surfaces. Examples include optical switches, shutters, scanners and locks. Typical reliability concerns include rubbing surfaces which promote wear and wear-induced adhesion

Most “successful” MEMS products are in Class I, because of high reliability and ease of qualification. Improved understanding of MEMS reliability physics and engineering is required to progress from Class I to HPM devices in Classes III and IV devices [30].

4. Failure prediction in HPMs

Different approaches have been proposed to predict failure modes in MEMS. The most common of which is the “failure-driven” approach [22], which predicts potential failures or risks by assessing the product or system throughout its life-cycle and identifying potential risks at each stage. This assessment is achieved by answering four questions:

- What is the application? e.g. mobile phone, car, space, defence, etc.
- Where? e.g. in a car to be placed under the hood, on a space shuttle, etc.
- What does the system see? This addresses the environment, e.g. pressure, vibrations, etc.
- What can go wrong?

3.2. Failure mode effect analysis (FMEA)

The last question, which is the core of the approach, is answered by conducting a systematic study known as Failure Mode Effect Analysis (FMEA).

FMEA is a well-established reliability tool, defined by the British Standards Institute standard BS5760 (Part 5) and has been used successfully to study reliability in different areas, such as automotive [26] and military equipment [27]. It has recently been implemented in microsystems applications.

FMEA has a number of advantages that makes it particularly suitable for microsystems:

- It has been shown to be an effective method for identifying potential failure modes and mechanisms because MEMS are effectively systems on micro scale [27]
- FMEA is a holistic approach that can be applied to the different stages of the life cycle of the product/system including manufacturing processes [27,34]
- The ultimate advantage of the FMEA analysis is that it is ‘proactive’ rather than ‘reactive’ [25,26]. Brainstorming potential failure modes enables the mitigation of risks before the design has been completed and before failures occur in the field. This results in significant costs and time savings by ensuring that the device is reliable, as shown in the Figure 2.2 [26]

However, FMEA requires that potential failure modes be prioritized. This is challenging for HPMs, taking into consideration the relatively maturity level of MEMS reliability in general, and extreme operational conditions in particular. This is combined with the lack of standard databases of material properties, mechanical and thermal performance, etc. at the micro scale.

To overcome such challenges, additional reliability tools can be combined with the FMEA analysis to generate the necessary data for addressing reliability concerns. Such tools are usually based on experimental testing. Two such tools accelerated aging, and numerical simulation are discussed below.

3.3. Accelerated aging

Accelerated aging (AA) is an experimentally-based reliability tool that is implemented to assess the robustness of a system. AA can be used in several with regards to the reliability of MEMS devices, based on a test-to-failure philosophy [20,27,32].

AA explores the concerns identified in the FMEA analysis by experimentally determining failure limits. Under normal operating conditions the prediction of lifetime on a statistically validated basis is very difficult. Therefore, failures have to be activated artificially by exposing the MEMS device to increased stress. AA is used as a ‘burn-in’ technique to evaluate infant mortality in MEMS devices. Weeding out devices with built-in weaknesses or defects is done by operating the devices for a short period of time under harsh environmental or drive conditions. AA is a design tool in the sense that it enables the MEMS designer to define the operation limits of the device: an “operating margin” where the device ceases to function and a “destruct margin” where permanent damage occurs.

Generally speaking, AA is a method to generate lifetime data in a short period of time. A study has shown that 70% of MEMS designers and suppliers perform accelerated life testing, and over 80% of those surveyed indicated that average lifetime for a MEMS device is 15 years [27]. If MEMS devices are expected to survive for this time, there has to be a practical method to assess their reliability without relying on statistical failure data that are rarely available.

3.4. Numerical Simulation

Numerical simulation, similarly to AA, is a reliability tool that is implemented to assess MEMS reliability when there is lack of statistical data. The use of numerical simulation on the micro scale is in its relatively early stages. Therefore, few examples are available in the literature which could be used to assess how it could assist in modeling failure modes.

Examples have been reported that simulate specific aspects of micro-scale reliability. They include electro-thermal modeling of temperature as a function of electrical excitation in actuators [25]; modeling stress versus displacement for micro-mirror arrays [37]; simulating MEMS mirrors [38].

Numerical simulation, in general, provides a method for predicting temperatures, stresses and dynamic responses in a device before the expensive, and time consuming, fabrication and testing processes begin, thus allowing for the design to be “optimized” earlier in the development process [33]. On the other hand, the accuracy of the method is currently limited by the lack of sufficient supporting test data [27].

5. Designing for reliability

FMEA, AA and simulation are reliability tools currently under development for MEMS devices across differing levels of maturity and success. However, no general framework yet combines these tools into an integrated design approach that can be implemented in designing HPMs.

An important motive for developing a general DfR approach for HPMs is cost considerations. Reliability costs are focused in two areas: late consideration of reliability problems [20] and the need for bespoke reliability tests [35].

With regard to the cost considerations, the early phases of product development are often dominated by considerations of design, functionality, producibility and costs. In many cases reliability issues are postponed to later stages. But the expense of fixing problems overlooked in an early phase increases drastically as product development moves onward [20]. Implementing a DfR approach at an early design stage would save the potential costs of later reliability issues.

Although it is difficult to develop generic tests for all types of microsystem devices, finding a common denominator and standardized testing - based on MEMS key failure mechanisms - are valuable to user community. A DfR approach would help in developing such standardized tests for MEMS, and users could carry out any additional reliability testing specifically needed for their applications, thus minimizing the cost of new technology implementation [36].

One DfR approach has been proposed [20] where reliability tools such as AA and simulation could be combined into a general reliability framework that covers different aspects of product development. The proposed approach comprises the following steps:

- Determination of significant materials and design parameters affecting the lifetime of a microsystem
- Understanding the physics behind the failure mechanisms
- Set-up of reliability models
- Deduction of design rules for increased reliability

Another approach has been proposed [25] in which MEMS reliability is based on the concept of “virtual prototyping”. This methodology is intended to be employed to achieve an optimum design before manufacturing, resulting in savings of time and money.

Virtual prototyping is a behavioral model methodology that considers the possible failure mechanisms before the completion of the design and before their occurrence in the field. The first step of this methodology is the creation of the virtual prototype, from the specifications, using modeling tools and materials databases. The reliability study can then be carried out by injecting already identified faults into the model and optimizing the MEMS design before its fabrication.

Similar to the methodological approach described earlier, a “science-based” reliability approach incorporating a solid base of modeling, simulation, and material science into a standard reliability methodology has been proposed [37]. The basic elements of this reliability method are:

- Design, model and fabricate
- Test structures and devices
- Identify failure modes and mechanisms
- Develop predictive reliability models (accelerated aging)
- Develop qualification methods

These approaches are all in the early stages of development and need a considerable amount of validation and refining. Generally speaking, a DfR approach or tool would require a combination of experimental testing, numerical simulation and material databases. All of these should be integrated together into a disciplined DfR approach that can:

- Anticipate failure modes at early design stages
- Assess and possibly quantify failure modes
- Reiterate on the product design to improve its reliability

6. Conclusions

This paper presents an assessment of the feasibility of a through-life approach for the development of high performance microsystems (HPMs).

HPMs are a promising technology that has gained significant interest in the past decade. Application areas include extreme operational environments, such as defense and space. However, reliability concerns associated with such conditions delay the progress of the technology from prototypes to market.

Research in reliability is at an early stage for HPMs, to some extent reflecting their lack of technological maturity. Reliability challenges for HPMs include component size, diverse materials, multiple science and engineering domains, diversity of applications, lack of failure examples, variety of extreme in-service conditions and difficulties in testing.

Failure prediction has been attempted for HPMs, following three approaches: failure mode effect analysis accelerated aging and numerical simulation. Design for reliability is an area that is still in its infancy for HPMs but several promising approaches exist.

Further research is required, in four areas in particular: design for reliability, design for manufacturability, degradation studies and failure risk mitigation.

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